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SIMULATING THE LUMINOUS AND THERMAL PERFORMANCE OF FENESTRATION SYSTEMS

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Introduction

During the last ten years, daylighting has become an increasingly important consideration for lighting designers, architects, and building owners. Besides the amenities that daylight offers,[3,9] it may significantly contribute to the reduction of electric lighting loads, especially in commercial buildings, where the largest portion of the lighting requirements occurs during the day. However, it is important that daylight admittance is controlled to prevent glare and negative impacts on cooling loads.[6]

As with electric lighting design, successful daylighting design requires means for predicting the luminous performance of fenestration systems. In other words, we need to predict daylight's contribution to the illuminance and luminance of interior surfaces. Daylight must be of sufficient quantity and quality for building occupants' visual comfort, visual performance, and aesthetic needs. Consideration of additional design criteria, such as thermal comfort and energy/cost implications, requires means for predicting the thermal performance of fenestration systems, so designers can balance and optimize the contribution of fenestration systems to lighting and thermal loads.

Background

There are two major methodologies for predicting the effects of fenestration systems on interior illuminance distributions. One is based on experimental techniques using scale models and the other is based on mathematical modeling through computer simulation. While experimental techniques with scale models have proven very effective for the prediction of the luminous performance of fenestration systems, they are time consuming and inflexible for the purposes of parametric studies. Also, high quality photometric measurements require significant investment in appropriate instrumentation. Moreover, such techniques do not allow the prediction of the thermal performance of fenestration systems. This is because they can only provide information about the illuminance and luminance of interior surfaces, and not on the total radiant flux transmitted and absorbed by the fenestration system. Mathematical modeling through computer simulation can be very fast and flexible, limited by the assumptions included in the theoretical models and the availability of suitable computer facilities. The accuracy of these assumptions is critical for the case of fenestration systems that incorporate optically-complex components, such as various shading devices, which scatter the incoming radiation and distribute it over the entire outgoing hemisphere.

Ideally, we could combine the strengths of experimental procedures and mathematical modeling for accurate, fast, and flexible prediction of both the luminous and thermal performance of fenestration systems. In this paper we describe such a methodology, which can be applied for the prediction of the luminous and thermal performance of any fenestration system. Also, we partially demonstrate the usefulness and the potential of our methodology using experimentally determined transmittance coefficients of commonly used Venetian blinds to compare the total transmitted luminous flux under various sky and ground conditions for horizontal and vertical orientation of the slats.

Methodology

The major innovation of our methodology is the representation of fenestration systems as electric lighting fixtures of varying output. This representation is achieved through detailed analysis of the radiant behavior of fenestration systems, encoded in the form of detailed solar-optical properties. We then treat each fenestration system as a "black box" of known radiant behavior; that is, we ignore the radiative phenomena within the fenestration system since we know the patterns of alteration at its borders.[18]

Solar-optical properties

In general, the radiant behavior of any object can be described as a function of the incoming and the outgoing directions of radiation and the wavelength of the radiation. While a complete spectral analysis would be most appropriate for describing the radiant behavior of fenestration systems, at this stage of the development of our methodology we are considering only the visible and the total solar spectra.

Definitions of solar-optical properties

Considering the possible combinations of single incoming and outgoing directions, and of the incoming and outgoing hemispheres, we define several solar-optical properties [**Figure 1**]:[4]

Directional hemispherical transmittance, $\tau(\theta_i,\zeta_i)$ (or reflectance, $\rho(\theta_i,\zeta_i)$), is defined as the ratio of transmitted (or reflected) flux collected over the entire hemisphere to essentially collimated incident flux incoming from the direction specified by the angles θ_i and ζ_i.

Bihemispherical transmittance, τ (or reflectance, ρ), is defined as the ratio of transmitted (or reflected) flux collected over the entire hemisphere to the incident flux from the entire hemisphere.

Bidirectional transmittance, $\tau(\theta_o,\zeta_o,\theta_i,\zeta_i)$ (or reflectance, $\rho(\theta_o,\zeta_o,\theta_i,\zeta_i)$), is defined as the ratio of transmitted (or reflected) flux collected over an element of solid angle surrounding the outgoing direction specified by the angles θ_o and ζ_o to essentially collimated incident flux incoming from the direction specified by the angles θ_i and ζ_i.

Hemispherical-directional transmittance, $\tau(\theta_o,\zeta_o)$ (or reflectance, $\rho(\theta_o,\zeta_o)$), is defined as the ratio of transmitted (or reflected) flux collected over an element of solid angle surrounding the outgoing direction specified by the angles θ_o and ζ_o to the incident flux from the entire hemisphere.

The bidirectional solar-optical properties provide the most detailed description of the radiant behavior of fenestration systems. All of the other solar-optical properties can be calculated from the bidirectional ones, by integration of the directional coefficients over the incoming and/or outgoing hemispheres.

Determination of solar-optical properties

To determine the thermal performance of a fenestration system it is necessary to know its bihemispherical transmittance and absorptance. To determine the luminous performance of a fenestration systems it is necessary to know its hemispherical-directional transmittance and reflectance. Since these properties involve the entire fenestration-facing hemisphere, they are functions of its luminance distribution which changes continuously during the day. Thus, it is appropriate to determine the directional-hemispherical and bidirectional solar-optical properties of fenestration systems and then integrate them over the luminance distribution of the fenestration-facing hemisphere. To measure such solar-optical properties we have developed two measuring facilities: an integrating sphere that measures directional-hemispherical transmittance[7] and a scanning radiometer that measures bidirectional transmittance and reflectance.[19]

For fenestration systems that incorporate more than one component (layer), for example a glazing layer and a shading device layer, we determine the total system properties from the properties of their layers, through appropriate computation.[13] This approach eliminates the need for measuring the solar-optical properties of all possible combinations of layers and, most important, it provides information about the absorbed radiation by layer, which cannot be determined from the bidirectional solar-optical properties of the whole fenestration system.

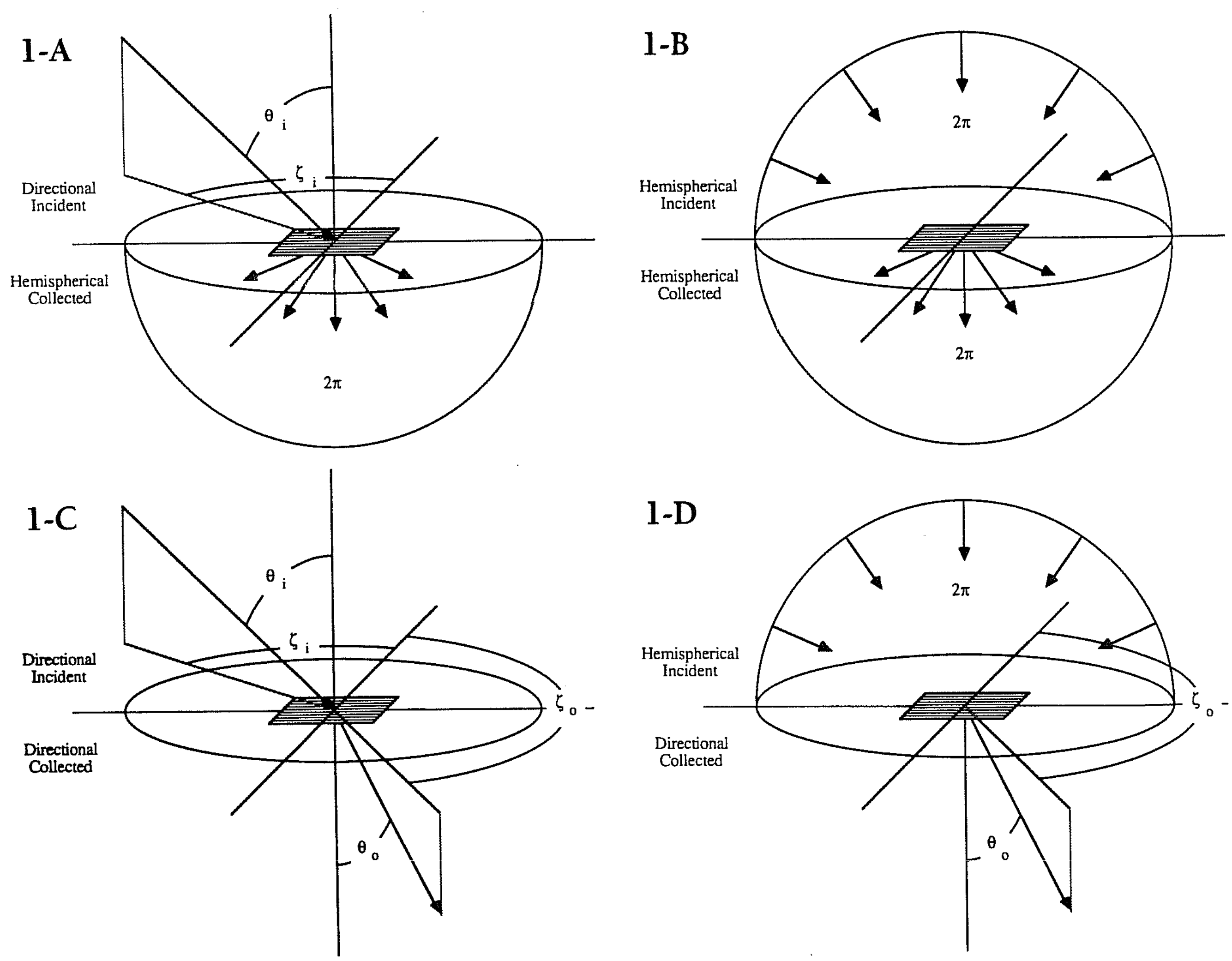


Figure 1—The concepts of the directional-hemispherical (A), bihemispherical (B), bidirectional (C), and hemispherical-directional (D) transmittance.

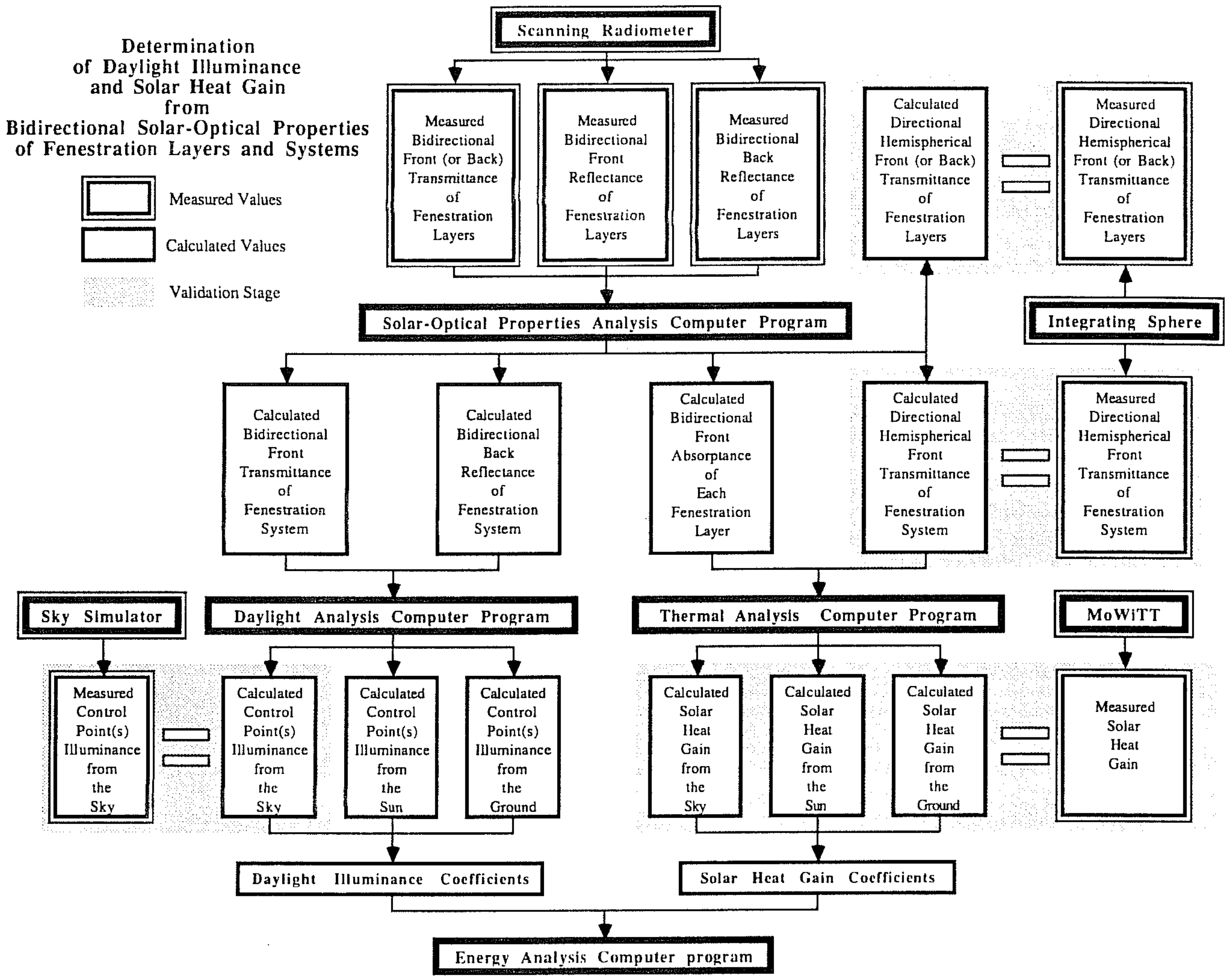


Figure 2—The experimental and computational process of simulating the luminous and thermal performance of fenestration systems.

Simulation of performance

Once the bidirectional solar-optical properties of a fenestration system are known, they can be integrated over the fenestration-facing hemisphere to yield the total transmitted and absorbed radiation as well as the outgoing candlepower distribution for the particular luminous distribution of the fenestration-facing hemisphere.

For operable fenestration components, such as Venetian blinds, we measure the solar-optical properties for many different setups, such as different slat angles for Venetian blinds, since each device setup has unique radiant behavior. To simulate the hourly luminous and thermal performance of an operable fenestration system throughout a full daily cycle, we select the properties for each hour that correspond to the appropriate device position based on its operational strategy.

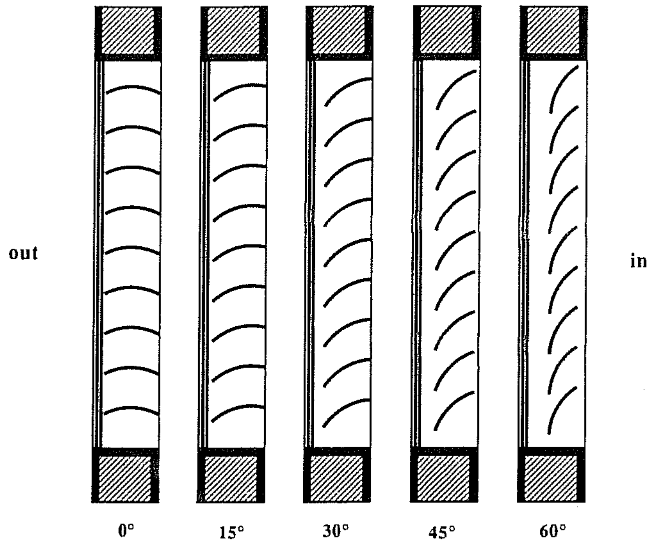
A daylight analysis computer model[10] and a thermal analysis computer model[14] then produce the appropriate input for an energy analysis computer model[1,2]. The entire experimental and computational process, shown in **Figure 2**, includes validation stages using our sky simulator[15] and our Mobile Window Thermal Test (MoWiTT) facility.[8]

Application Example

In order to partially test and demonstrate the usefulness and the potential of our methodology, we applied it to determine the total transmitted luminous flux through an operable slat-type shading device under various sun, sky and ground conditions.

Slat-type shading devices are among the most popular in commercial buildings. Previous simulations of their radiant performance have been based on geometrical modeling.[11,12,16,5,17] Such modeling incorporates assumptions about the slats' geometry and reflectance. Usually, slats are assumed to be flat with perfectly diffusing finish, while in reality they are usually curved, like Venetian blinds, and most commercially available slat finishes have a substantial specular component to their reflectance.

The slat-type shading device that we used was a Venetian blind system composed of 1 inch wide aluminum slats with a semi-specular grey finish of approximately 40 percent reflectance. The distance between the slats was 0.75 inches. We measured the directional-hemispherical transmittance of the Venetian blinds and then used the measured coefficients to simulate the total transmitted flux during typical winter and summer days for several window orientations. To further demonstrate the importance and the necessity of detailed solar-optical properties for performance simulation, we used the same measured data in two different simulations, to examine the performance differences be-



The slat angles of the Venetian Blinds that were considered for the directional-hemispherical transmittance measurements.

tween blinds with horizontal slats and blinds with vertical slats.

Experimental procedures

Using our large integrating sphere,[7] we measured the directional-hemispherical transmittance of a 2 ft x 2 ft sample of the Venetian blinds. Measurements were taken for five slat angles downwards from the fully open position. These were 0 degrees (fully open position), 15 degrees, 30 degrees, 45 degrees, and 60 degrees [**Figure 3**]. The incoming directions covered were at intervals of 15 degrees in both the relative azimuth, ζ, and the incident angle, θ [**Figures 4** and **5**].

The results from the measurements are shown in **Figure 6**. From these figures we can see that the transmittance can vary significantly (between approximately 0.1 and 0.9), depending on the direction of the incoming radiation and, of course, on the slat angle of the Venetian blinds.

The same transmittance coefficients were used to model the performance of both horizontally and vertically oriented slats, for vertical windows. With horizontal orientation of the slats, the sky directions correspond to relative azimuths 0 degrees through 90 degrees and 270 degrees through 360 degrees, while the ground directions correspond to relative azimuths 90 degrees through 270 degrees. With vertical orientation of the slats, the sky directions correspond to relative azimuths 0 degrees through 180 degrees or 180 degrees through 360 degrees (values are symmetrical), the rest corresponding to the ground directions.

Computational procedures

For the purposes of this study we assumed that the shading devices would be adjusted to always block direct sunlight penetration with slats as open as possible. We considered both continuous and stepped tilting of the slats at 15 degrees increments. Two kinds of comparisons were made for horizontal and vertical orientations of the slats:

- comparison of the slat angles for solar blocking and
- comparison of the total transmitted daylight flux.

The angle of the slats gives information about the potential of the shading system to provide view. The total daylight flux transmitted indicates the potential for daylight contribution to lighting needs and the impact of solar heat gain on heating and cooling loads.

The simulation was performed for every daytime hour of a typical winter day (February 12th) and a typical summer day (July 2nd). For the winter day we examined two different ground reflectance values, one for grass/soil (0.2) and one for snow (0.8). The weather data were from Madison, Wisconsin. Since we assumed that shading systems are used to control direct solar radiation, only clear-sky luminance distributions were considered, and the slats were retracted when the sun was not in the fenestration-facing hemisphere. Five different orientations were examined: north, northeast, east, southeast and south. The southwest, west and northwest orientations were not examined, because they are symmetrical to the southeast, east and northeast, with respect to the relative positions of the sun and the fenestration system.

For the hourly performance simulation, the transmitted

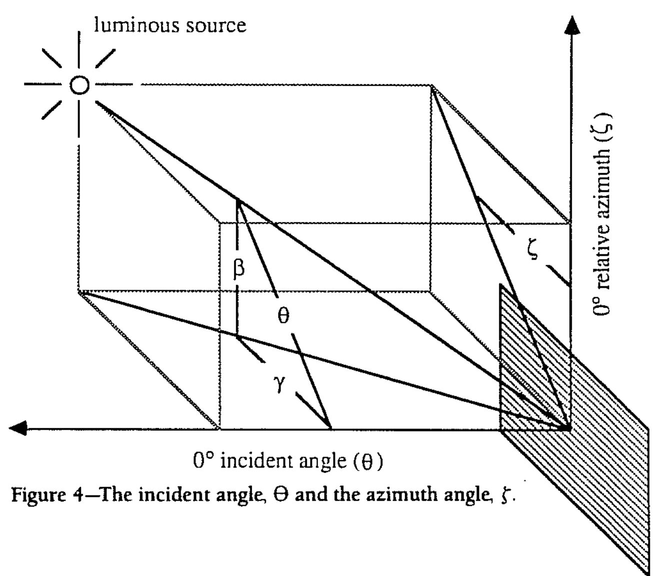


Figure 4—The incident angle, Θ and the azimuth angle, ζ.

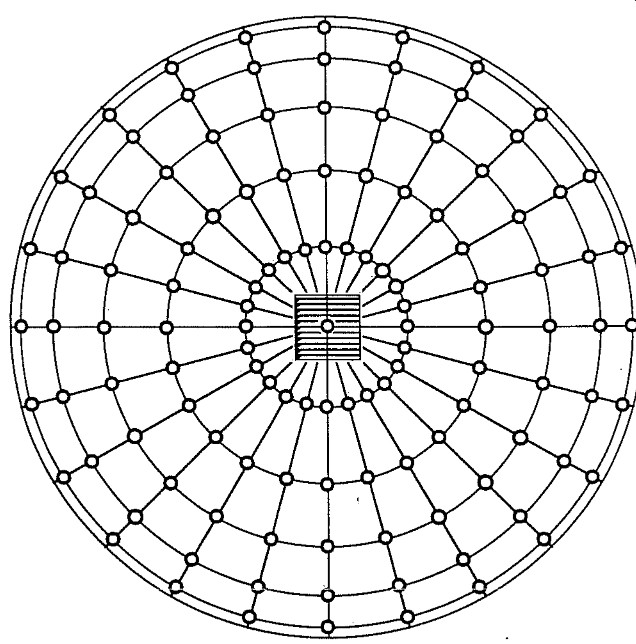
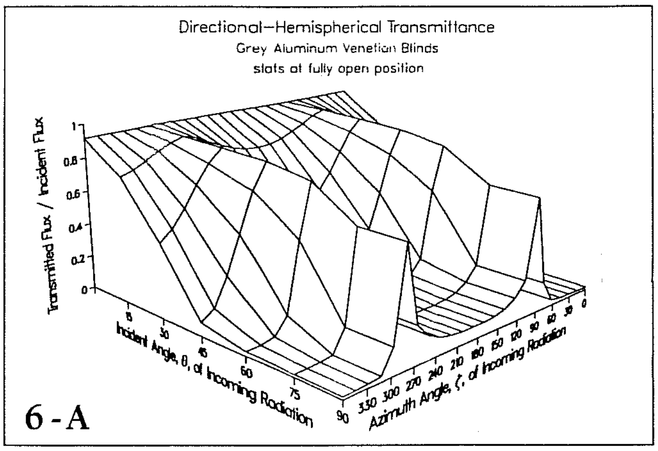
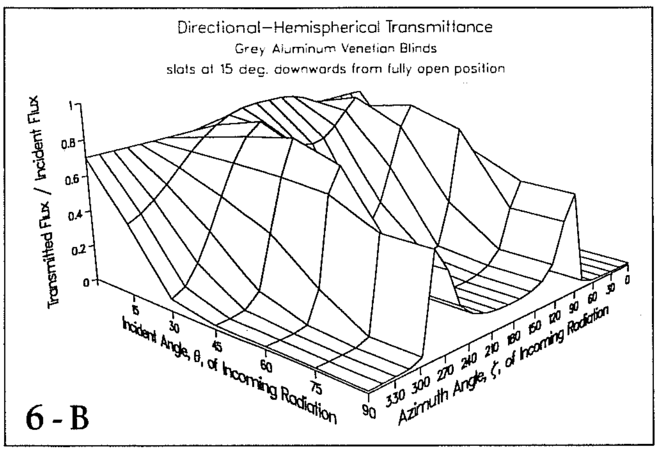


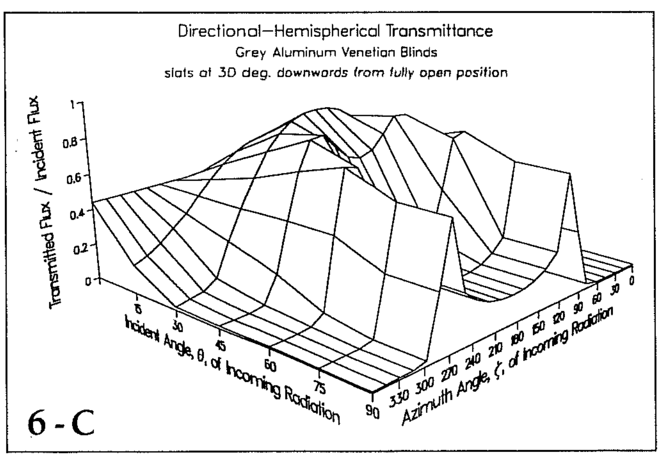
Figure 5—Projection of the positions of the luminous source that were considered for the directional-hemispherical transmittance measurements.



6-A



6-B



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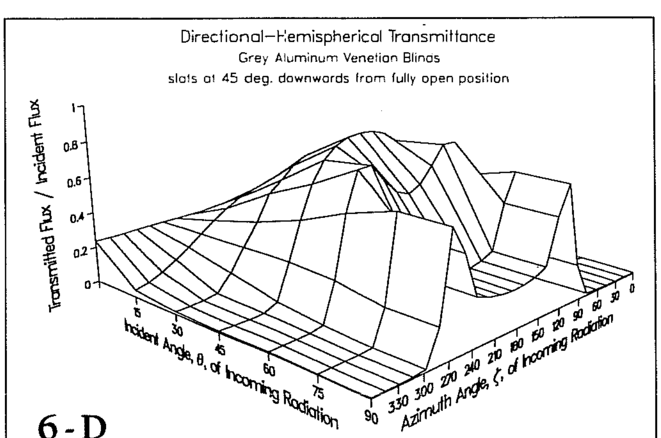
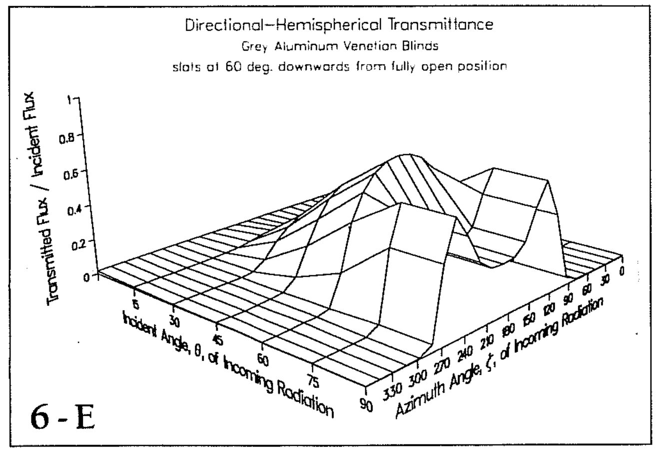


6-D



6-E

Figure 6—Directional-hemispherical transmittance coefficients of the Venetian blinds for 0° (A), 15° (B), 30° (C), 45° (D), and 60° (E) slat angle downwards from the fully open position.

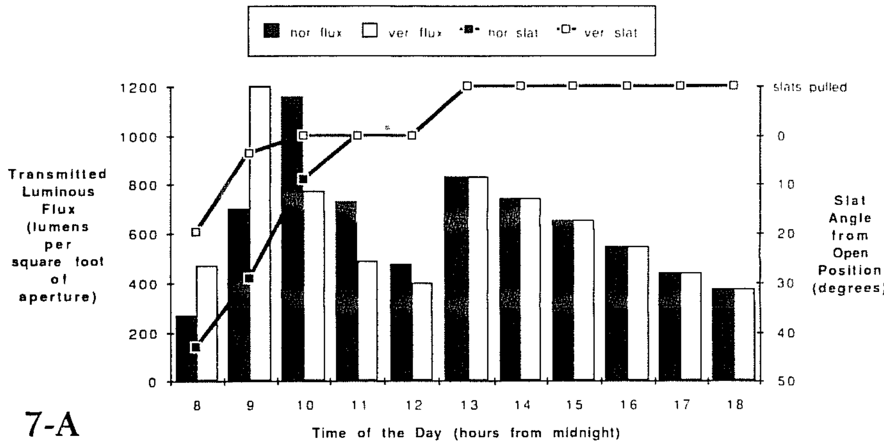
flux from sky and ground was determined by integration over the sky and the ground, using 15 degree intervals for both relative azimuth and incident angle. During the integration we applied directly the measured transmittance coefficients for each angle-dependent sky and ground element. The transmittance coefficients to be used for the specific slat angle for each hour were determined by interpolating between the closest slat angles considered in the measurements. The direct solar illuminance and the luminance distribution of the sky were calculated according to the procedures followed in the DOE-2.1B energy analysis program.[20]

Simulation results

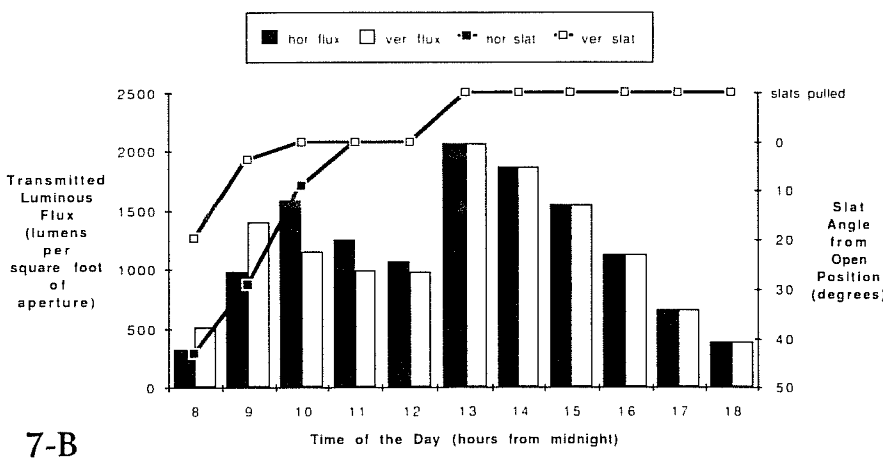
Some of the results from the performance simulations considering continuous tilting of the slats are shown in **Figures 7** and **8**, for east and south orientation respectively, where the bar charts show the total luminous flux transmitted through horizontal and vertical slats (left scales) and the line charts show the angle of the slats from the fully open position (right scales).

It should be noted that the results of these simulations are for the purposes of demonstrating our methodology and have not been validated with measurements of the actual performance under real sky and ground conditions. This was our first attempt to combine detailed solar-optical properties with analytical procedures and it was not meant to provide a complete, accurate analysis of the performance of Venetian blinds.

The results from the simulation show that the total transmitted flux through a fenestration system indeed depends strongly on the combined consideration of the luminance distribution of the fenestration-facing hemisphere and the radiant behavior of the fenestration system. This becomes obvious especially for the cases where both vertical and horizontal slats are fully open, transmitting different luminous flux. In some cases, as, for example, during the summer midday hours for south orientation, the significantly tilted vertical slats transmit more daylight than the fully open horizontal slats. This emphasizes the impact of the luminance distribution of the fenestration-facing hemisphere, combined with the directional transmittance of the



7-A



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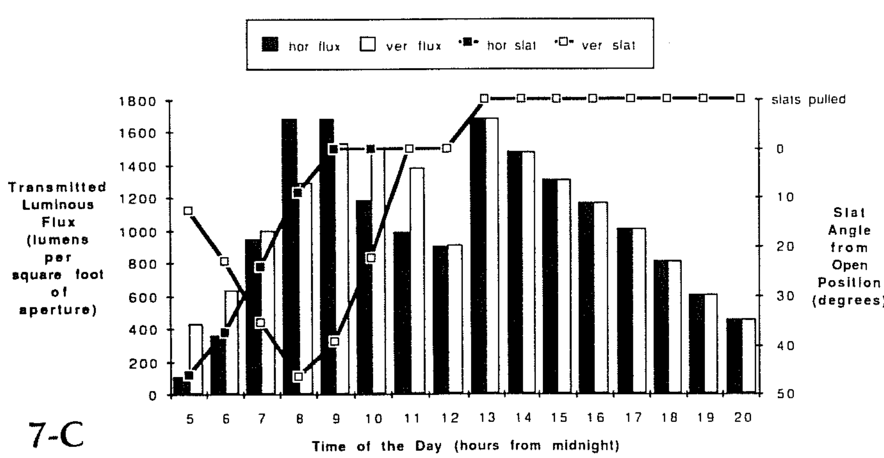

7-C

Figure 7—Transmitted fluxes and slat angles for an east-facing window during a typical winter day (A), a typical winter day with snow on the ground (B), and a typical summer day (C), considering continuous tilting of the slats. The terms *hor flux* and *ver flux* refer to the transmitted fluxes and the terms *hor slat* and *ver slat* refer to the slat angles, for horizontal and vertical orientation of the slats, respectively.

fenestration system.

Another powerful feature of our approach is the capability of differentiating between the various radiation sources, in this case between the sun, the sky, and the ground. This capability contributes greatly to our understanding of the fenestration system's performance. **Figure 9**, for example, contributes to our understanding of the summer midday differences for south orientation, indicating that these are mainly due to the transmitted direct sunlight, through interreflections between the slats. The high-altitude midday summer sun cannot contribute significantly to the transmitted flux through the horizontal slats, since it directly illuminates only a small fraction of the width of each slat. However, for the case of the vertical slats, the operation strategy that tilts the slats for solar blocking, while trying to maintain maximum openness, means that the whole width of each slat contributes to the transmission of direct sunlight.

Our approach allows for easy determination of the effects not only of context parameters, such as ground reflectance, but of design parameters as well, such as the the operation strategy for operable shading devices. **Figure 10** shows the south orientation results for the stepped tilting of the slats at 15 degree increments, which are almost identical to the corresponding results for continuous tilting during the summer day, but significantly different from the corresponding results for continuous tilting during the winter day.

Conclusions and Future Directions

We described our methodology for the determination of the luminous and thermal performance of fenestration systems of arbitrary complexity, treating them as electric lighting fixtures of continuously varying output. We demonstrated the usefulness and the potential of our methodology using measured directional-hemispherical transmittance of commonly used Venetian blinds to determine the total luminous flux transmitted for vertical and horizontal orientation of the blinds' slats, throughout typical winter and summer days. Although we intend to use the total flux properties of fenestration systems for the determination of solar heat gain, the total transmitted luminous flux can also be used with coefficient-of-utilization methods for determining work-plane illuminance.

Currently, we are fine-tuning the measurement and calculation process to determine bidirectional solar-optical properties and transmitted candlepower distributions under any sun, sky and ground conditions. Using these new facilities we will create libraries of measured solar-optical properties for a large variety of commonly used fenestration components. We will then be able to simulate the performance of any combination of fenestration components for any application, geographic location, and orientation of fenestration.

Although the process of measuring and organizing such detailed properties is long, especially for bidirectional properties, these properties, once determined, can be used for any daylight application. Moreover, the computation time involved in the analytical routines is very short, since it involves only the selection of the appropriate transmittance, reflectance, or absorptance coefficients, rather than time-consuming calculation of the radiant phenomena within the fenestration system. Most important, our methodology can be used to simulate the luminous and thermal performance of any fenestration system, in an accurate and consistent way.

Acknowledgements

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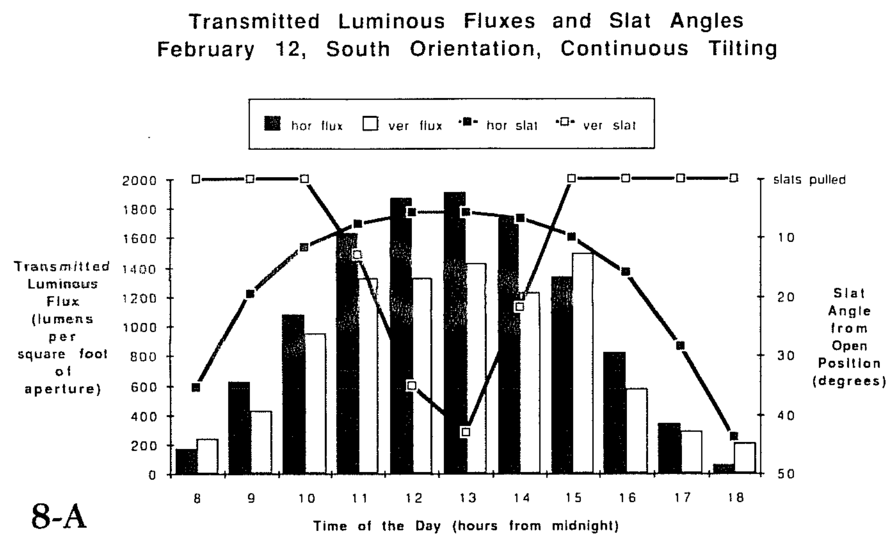

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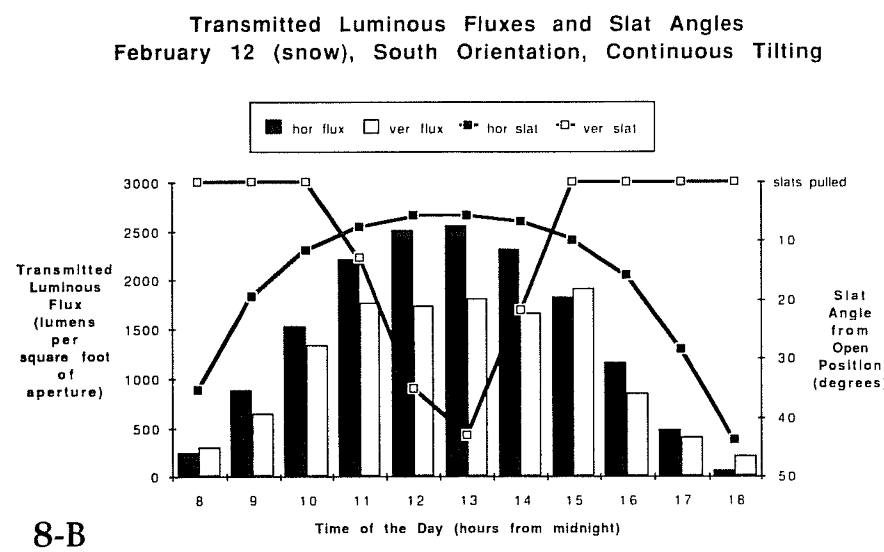

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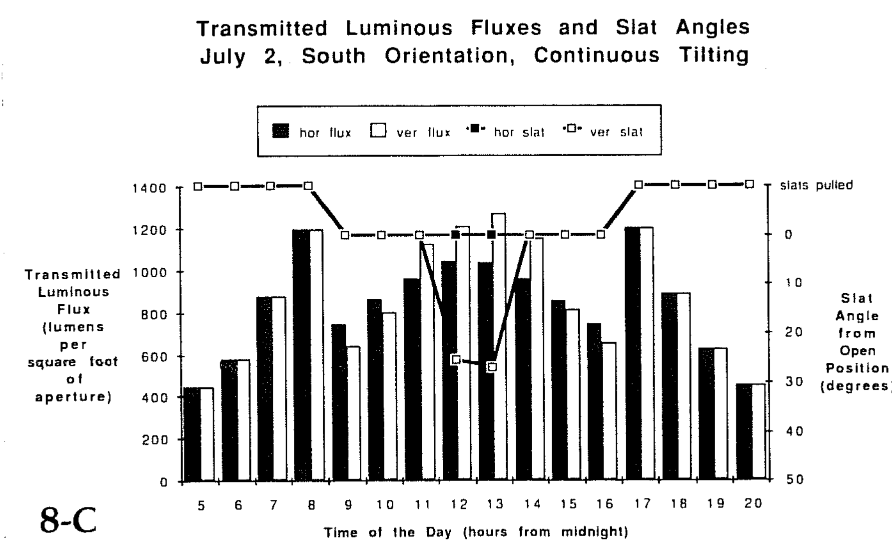
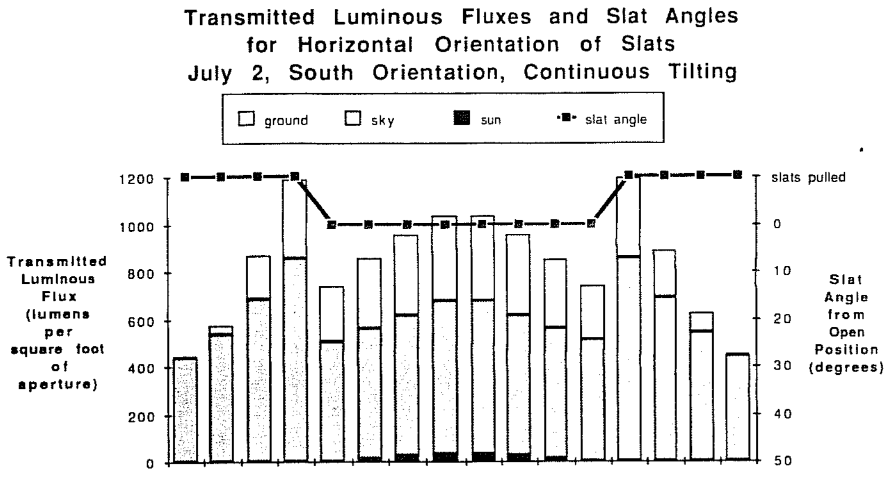


8-C

Figure 8—Transmitted fluxes and slat angles for a south-facing window during a typical winter day (A), a typical winter day with snow on the ground (B), and a typical summer day (C), considering continuous tilting of the slats. The terms *hor flux* and *ver flux* refer to the transmitted fluxes and the terms *hor slat* and *ver slat* refer to the slat angles, for horizontal and vertical orientation of the slats, respectively.



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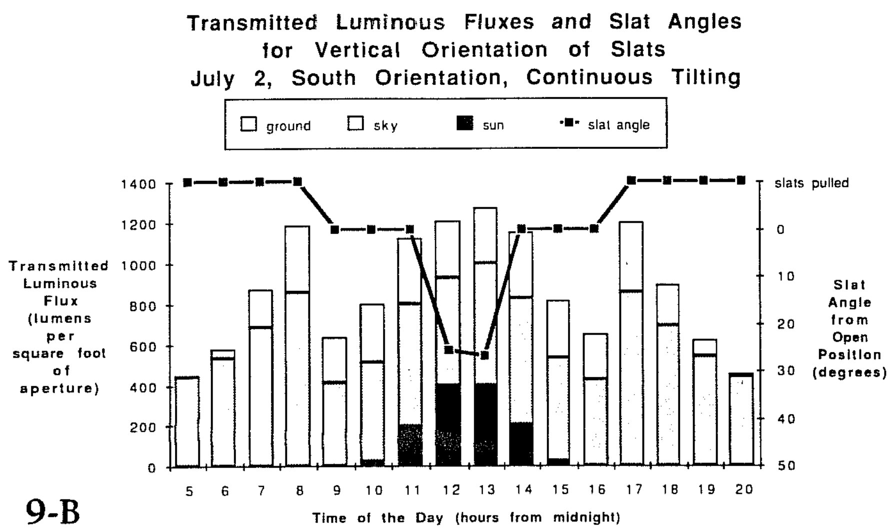

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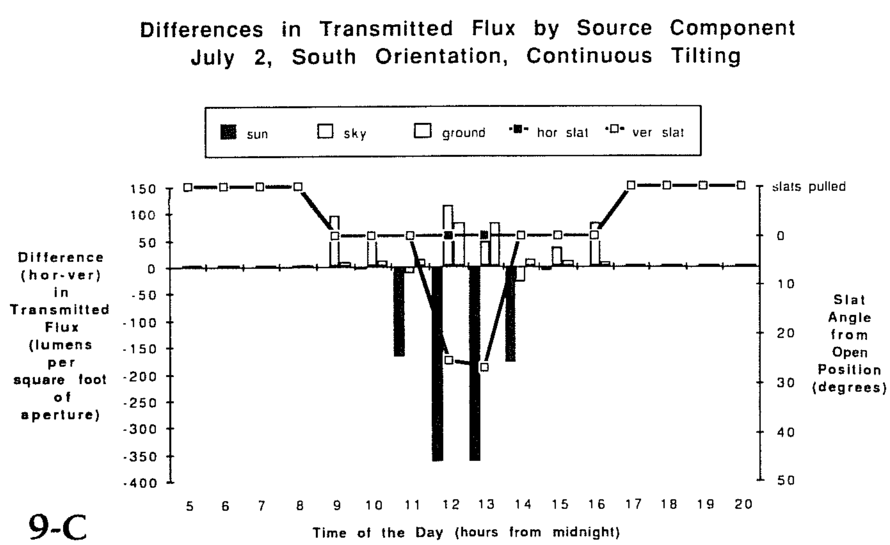

9-C

Figure 9—Transmitted fluxes by source component through horizontal slats (A) and through vertical slats (B), and slat angles and differences in transmitted fluxes by source component (C) for a south-facing window during a typical summer day, considering the continuous tilting of the slats. The terms *hor flux* and *ver flux* refer to the transmitted fluxes and the terms *hor slat* and *ver slat* refer to the slat angles, for horizontal and vertical orientation of the slats, respectively.

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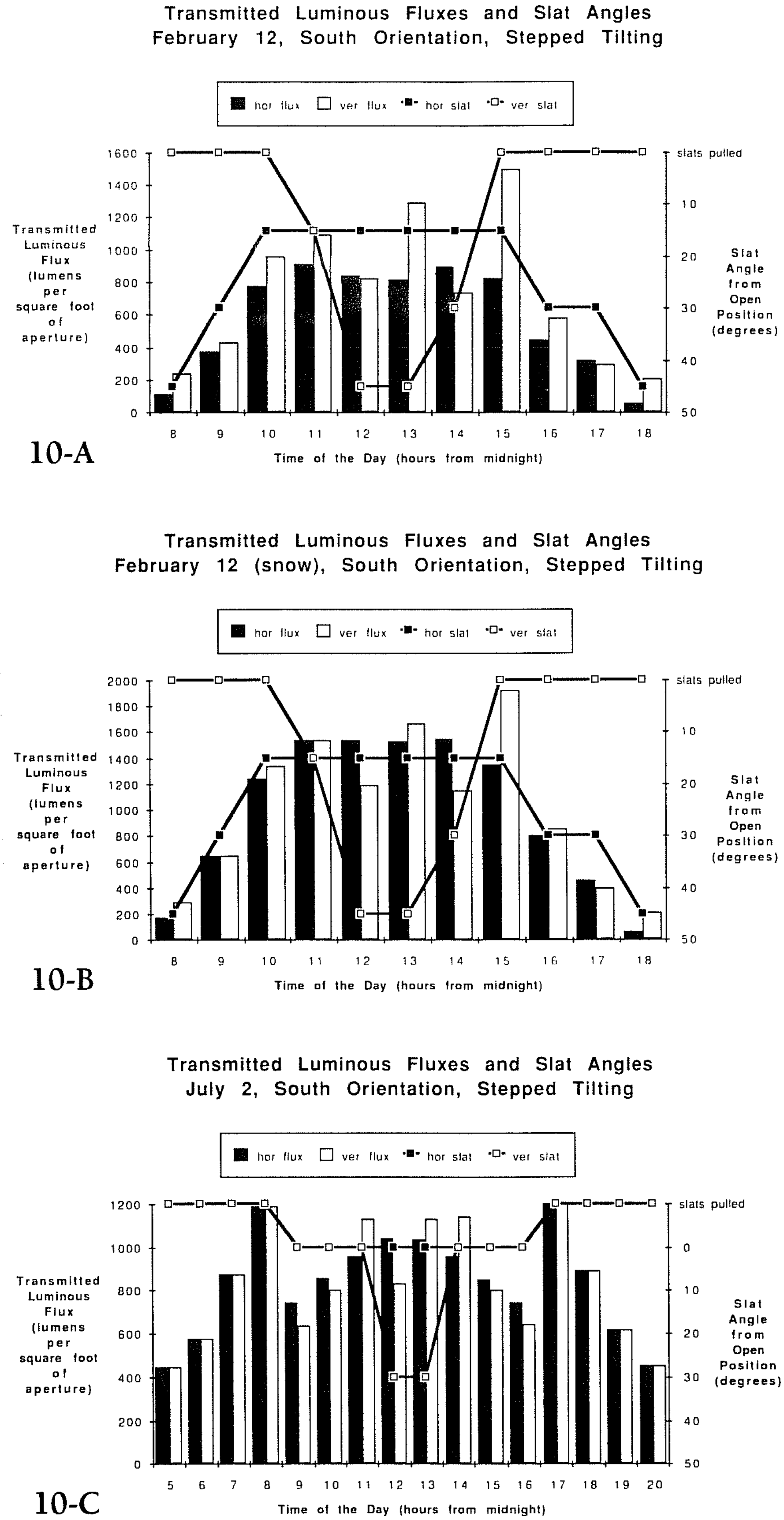

Figure 10—Transmitted fluxes and slat angles for a south-facing window during a typical winter day (A), a typical winter day with snow on the ground (B) and a typical simmer day (C), considering stepped tilting of the slats. The terms *hor flux* and *ver flux* refer to the transmitted fluxes and the terms *hor slat* and*ver slat* refer to the slat angles, for horizontal and vertical orientation of the slats, respectively.